

Generator Voltage Stabilisation for the Series-Hybrid Vehicle

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Abstract

This paper presents a simple, robust controller for use in speed control of an internal combustion engine for series-hybrid electric vehicle applications. Particular reference is made to the stability of the rectified DC link voltage under load disturbance and potentially inaccurate system models. In the system under consideration, the primary power source is a 4-cylinder normally aspirated gasoline internal combustion engine, which is mechanically coupled to a three-phase permanent magnet AC generator. The generated AC voltage is subsequently rectified to supply a lead-acid battery, and permanent magnet traction motors via three-phase full bridge power electronic inverters. Two complementary performance objectives exist. Firstly to maintain the internal combustion engine at its optimal operating point, and secondly to supply a stable 42V supply to the traction drive inverters. Achievement of these goals minimises the transient energy storage requirements at the DC link, with a consequent reduction in both weight and cost. These objectives imply constant velocity operation of the internal combustion engine under external load disturbances and changes in both operating conditions and vehicle speed set-points. An electronically operated throttle allows closed loop engine velocity control. System time-delays and non-linearities render closed loop control design extremely problematic. A model based controller is designed and shown to be robust in controlling the DC link voltage, resulting in well-conditioned operation of the hybrid vehicle.

Key words: Automotive, Model-Reference Control, Time-Delay, Hybrid Vehicles

Introduction

The series-hybrid electric vehicle drivetrain [1] consists of [2] petrol internal combustion (IC) engine, AC generator, DC rectification, battery energy storage, three-phase inverter and traction drives (Fig. 1). The stability of the DC link between the

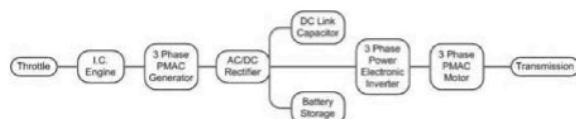


Fig. 1. Series-hybrid electric vehicle drivetrain.

AC/DC rectifier and the traction motor inverter

drive is operationally critical whether the prime mover be a petrol or diesel IC engine [3]. Firstly a prime objective for operation of the traction drives is to deliver smooth, ripple-free torque. Controllers for this purpose rely on a stable DC link supply. Of particular importance is its ability to reject both dynamic and static loads from the traction drives and also an ability to absorb excess energy under regenerative braking regimes. A direct advantage of maintaining the integrity of the DC link voltage is the associated maintenance of the IC engine at its optimal operating point in terms of fuel efficiency and pollutants [3]. Again, the rejection of dynamics from drive loading is instrumental in achieving this goal.

The control system for the series-hybrid electric vehicle (SEV) has both cascaded and nested structures, and consists of a velocity set-point controller for the IC engine via an electronically actuated throttle, and current control loops around the traction drive units (Fig. 2). There are a variety of power

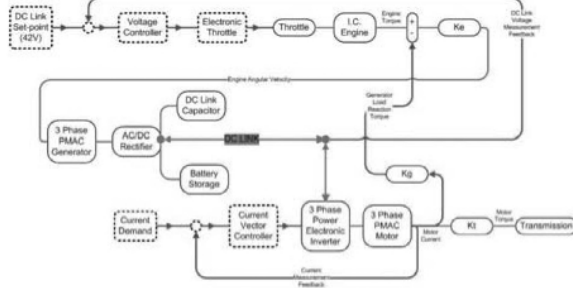


Fig. 2. Series-hybrid electric vehicle control structure.

control strategies applied to hybrid electric vehicle (HEV) powertrains [4],[5] which generally try to achieve a number of goals in a four cost function [2],

- maximise fuel economy
- minimise emissions
- minimise system costs
- maximise driving performance.

Choice of operating point

Of particular importance in this analysis is the twin goals of maximising fuel economy and minimising emissions such as hydrocarbons (HC) and carbon monoxide (CO). The experimental fuel consumption and efficiency of a typical [6] four cylinder four-stroke spark ignition engine with a nominal size of 1600cc. running on 91 octane gasoline are shown in figures (3,4).

Brake thermal efficiency (BTE) is calculated as

$$BTE = \frac{Pe}{\dot{m}_f LHV}, \quad (1)$$

where Pe is effective power, \dot{m}_f is the fuel mass flow rate, and LHV the lower heating value of the fuel. B the engine fuel consumption and thermal efficiency, have a corresponding optimal speed of 1800 rpm with respect to minimisation of fuel consumption and maximisation of efficiency.

With respect to emissions, CO decreases steadily through the experimental range, whereas HC is relatively stable above 1600 rpm. The choice of operating point thus presents a tradeoff between objectives. HC emissions require an operating point above

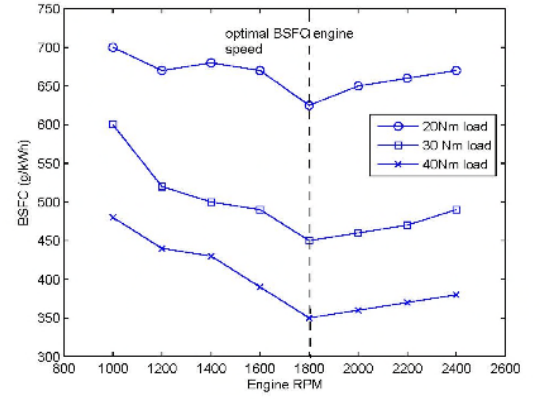


Fig. 3. Engine fuel consumption at varying loads

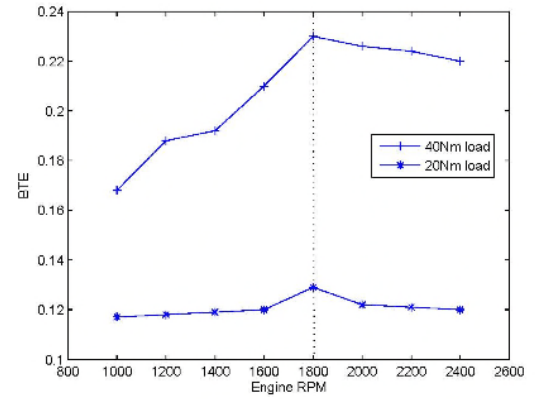


Fig. 4. Engine brake thermal efficiency at varying loads

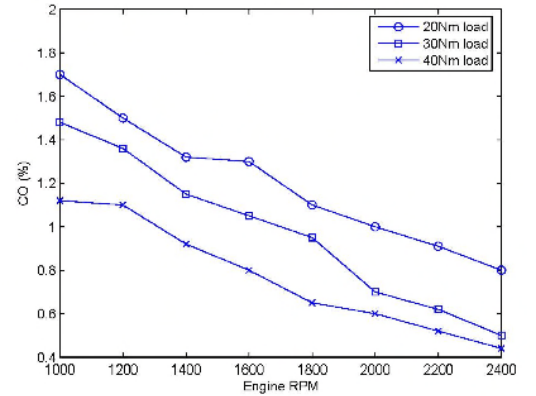


Fig. 5. Exhaust CO percentage at varying loads

1600 rpm, fuel consumption and efficiency is optimal at 1800 rpm. CO emissions are declining by approximately 0.05%/200rpm in this region. It was thus decided to trade-off CO emissions and fuel economy

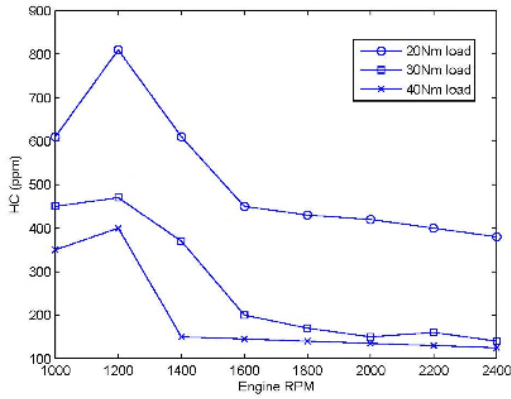


Fig. 6. Exhaust HC (ppm) at varying loads

at 2000rpm, gaining a reduction in emissions, for a small reduction in efficiency.

1. Generator voltage control

Stable generator output voltage requires control authority over engine speed. A number of methodologies for idle speed control (ISC) have been presented in the literature [10]. The primary motivation for ISC is to maintain a selected idle speed while rejecting torque disturbances such as power steering, alternator and automatic transmission loads.

In most production vehicles, the amount of air is controlled by a throttle bypass valve, sometimes augmented by additional valves actuated by an accessory load signal [11]. Alternatively, it is possible to directly control the throttle by direct electronic means rather than by mechanical linkages [12],[13]. Air control provides large authority over the engine, however it is subject to intake manifold dynamics and intake-to-torque time delays. Direct control of the spark ignition timing provides a high bandwidth-low delay approach. However spark control has rather limited authority since excessive retardation of the ignition can cause combustion instabilities.

In the hybrid electric vehicle under consideration here, it is desired to produce a low-cost implementation of the control structure, and hence direct control of the throttle by electronic means is identified as the preferred technology if the inherent system delays can be overcome to produce a reliable speed controller. This is reinforced by the fact that a typical production ISC controller includes a PID loop for air control, a proportional loop for the

spark control, feedforward loop for accessory loads, and other ad hoc loops for a variety of environmental compensation schemes.

The main characteristics of spark ignition engines is that they are highly nonlinear with significant time delay between throttle and torque production. The main objective of this research is to produce low-cost stable engine angular velocity control with good disturbance rejection characteristics. Torque based control methods [14], [15], generally rely on high precision feedback data such as cylinder pressure sensors, however cycle-to-cycle fluctuations coupled with low resolution crank angle measurements can pose problems for the stability of any closed loop control scheme. This often leads to the complicated implementation of further inner compensation schemes.

1.1. Smith Predictor

The general limitation of tuning rules for PID controllers is that they are derived for delay-free systems. For the system under consideration, the compound time delay between control actuator signal and torque production initiation at 2000rpm was found experimentally to be 980ms with a variability of $\pm 50ms$. Under such circumstances, a PID controller is extremely difficult to tune by standard tuning rules. A stable controller was eventually identified by trial and error with hardware in the loop. The performance of the controller is shown in figure 7. The experimental setup is discussed more fully in later sections of this paper. The regulator was attempting to stabilise the generated dc voltage at 42V, the performance was as follows:

- Mean voltage 39.4V
- Standard deviation 3.27V

Of particular note is the 9s delay initialising to a quasi steady state condition. The chosen controller was a PD type with gains of 0.04 and 0.01 respectively. Any larger gain combinations or addition of an integral component to the controller resulted in better mean voltage values but increasing oscillatory response. In figure 8 the PID gains have been set at 0.04, 0.01 and 0.01 respectively. The integral component has improved the mean voltage at the expense of large voltage ripple. The performance of this controller was:

- Mean voltage 41.83V
- Standard deviation 4.38V

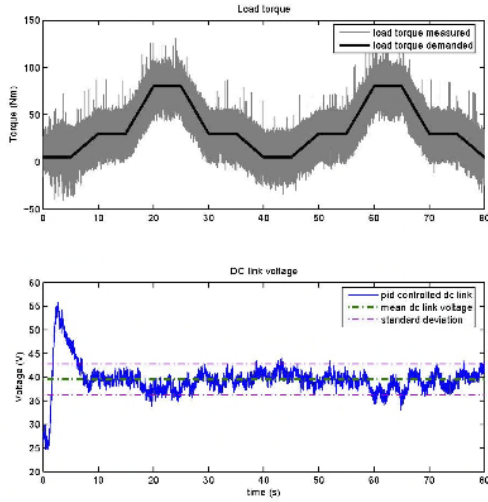


Fig. 7. Regulation of hybrid dc link voltage with PD controller

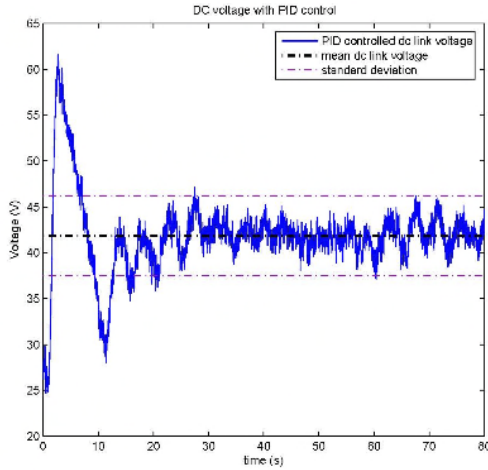


Fig. 8. Regulation of hybrid dc link voltage with PID controller

This motivates the design of a predictive controller such as the Smith Predictor [8], [9]. The predictor generally utilises a model of the plant characterized into a linear transfer function accompanied by a time delay. A model is used to simulate the delayed and undelayed states of the plant, subsequently the real plant output is canceled by the delayed state, and the undelayed state is used as the feedback signal for the plant controller (fig 9). The transfer function of the plant and Smith Predictor can be written as [7]

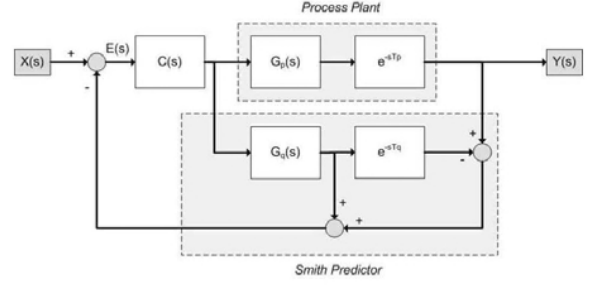


Fig. 9. Smith Predictor control structure for system with time delay.

$$\frac{Y(s)}{X(s)} = \frac{C(s)G_p(s)e^{-sT_p}}{1 + C(s)G_q(s) + C(s)[G_p(s)e^{-sT_p} - G_q(s)e^{-sT_q}]} \quad (2)$$

Hence if the model parameters exactly match the plant, equation (2) simplifies to

$$\frac{Y(s)}{X(s)} = \frac{C(s)G_p(s)}{1 + C(s)G_p(s)} e^{-sT_p}. \quad (3)$$

The predictor removes the time delay effects from the control loop, converting the corresponding control design to a delay free problem. The process model $G_p(s)$ contains a dead-time $T_p > 0$, with controller $C(s)$, and a loop containing a process model $G_q(s)e^{-sT_q}$.

The feedback signal is given by

$$Y_{FB}(s) = G_q(s)E(s)C(s) + (G_p(s)e^{-sT_p} - G_q(s)e^{-sT_q})E(s)C(s) \quad (4)$$

Assuming perfect modeling of the plant and delay, then

$$Y_{FB} = G_q(s)E(s)C(s). \quad (5)$$

Since

$$E(s)C(s) = \frac{1}{G_p(s)e^{-sT_p}}Y(s) \quad \text{and,} \quad G_q(s) = G_p(s) \quad (6)$$

then,

$$Y_{FB} = G_q(s) \frac{1}{G_p(s)e^{-sT_p}}Y(s) = e^{sT_p}Y(s). \quad (7)$$

Thus in the time-domain, $Y_{FB}(t) = y(t+T)$ which is the prediction of the output signal.

1.2. Smith predictor engine model

The implementation of a predictive controller to overcome the significant time delays inherent in the engine requires a model which is representative of the engine dynamics and time delay [10]. In this case, for simplicity and ease of implementation, the adopted model (figure 10) was a set of structures linearised [16] around the operating speed of interest, which relates output torque changes to changes in fuel, spark and throttle [17].

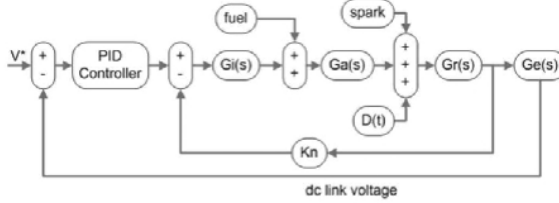


Fig. 10. Linearised engine / generator model

Where V^* is the required dc link voltage, $G_i(s)$ is the inlet manifold dynamics, $G_a(s)$ is the combustion delay, $G_r(s)$ is the lumped rotational dynamics for the combined system, $G_e(s)$ is the generator electrical dynamics, Kn is the pumping dynamics, and $D(t)$ is the time-varying load from the traction motors which are reflected into the ic engine as reaction torque from the generator. Tests for obtaining the model parameter values [18], consisting of throttle, spark and load inputs resulting in perturbation response of the generator voltage level. This method enables direct evaluation of the model parameter values.

In particular, tests were carried out to produce linearised models not only at the nominal operating point of $2000rpm$, but via designed experiments between $1500 - 2000rpm$. This enabled the implementation of a parameter lookup table giving a linearised model over a range of operating conditions. The parameters of the model are currently subject to a confidentiality agreement.

2. Results

The experimental results presented in this paper (figures 7,8, 12) were carried out under PID or PD control which was tracking a $42V$ voltage command. In each case, the disturbance torque reflected back to the generator followed the profile presented in figures 7, 12, with a peak disturbance of $80Nm$. The implementation of the predictive controller improves

the generator stability considerably, from a worst case of mean voltage $39.4V$ and standard deviation of $4.38V$ to a mean voltage of $41.64V$ and standard deviation of $1.2V$ for the predictor compensated system (figure 12).

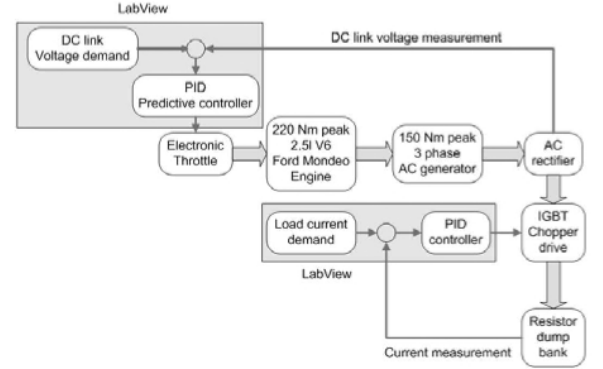


Fig. 11. Experimental rig.

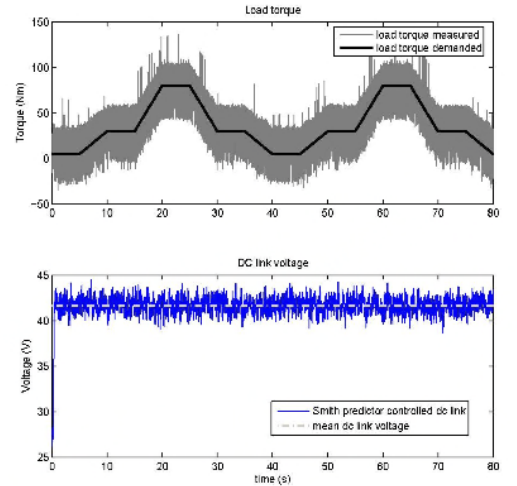


Fig. 12. Engine torque disturbance and generator output voltage.

The implementation of the Smith Predictor significantly reduced the voltage ripple generated by the hybrid powertrain. In particular the use of a simplified linearised model has shown itself to be effective, especially considering the problems of integration and development into a real-time controller.

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